Survival Probabilities of Disoriented Chiral Domains in Relativistic Heavy Ion Collisions

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INTRODUCTION

Disoriented chiral condensates (DCC) were recently proposed as potential signatures for chiral symmetry restoration [1,2, 3,4]. In the theory of DCC formation, the explicit chiral symmetry breaking which occurs during the phase transition from a plasma phase, where all masses are zero, to normal nuclear matter, where particles have mass, is accompanied by the formation of extended domains in which the chiral field is misaligned with respect to the true vacuum direction.

This phenomenon has been explained in the context of the linear sigma model. Here the isospin symmetry is not conserved during the occurance of explicit chiral symmetry breaking, due to a slight tilt in the potential. This leads to to an oscillatory behavior of the long wavelength modes of the pion field in the sigma model, which subsequently causes the emission of pions of a specific isospin so that the field can regain its isospin symmetric ground state. In Jorgen Randrup's contribution to this conference [5] the theoretical aspects of the DCC formation are described in more detail.

At the time of emission the content of a disoriented domain should behave like a Bose condensate. Typical features of a Bose condensate, sometimes referred to as pion laser, are the emission of very low momentum, coherent pions and an increase in pion multiplicity in addition to the already mentioned isospin asymmetry. These effects were described in detail by Pratt [6]. Domain formation is a non-perturbative phenomenon which should occur during any transition. The main question for experimental high energy physics is whether the domains formed are large enough and sufficiently long-lived to be detected.

The prime accessible signature of DCC formation is the ratio of neutral to charged pions in a certain range of phase space, which should exhibit non-statistical isospin fluctuations. If one defines the parameter f as the ratio of number of neutral pions over the number of all pions emitted from the collision, then a standard isospin distribution will lead to a value sharply peaked around 0.33, whereas a DCC sample exhibits a probability function described by P(f) = $1/2\sqrt{f}$. The determination of f requires a

good measurement of the number of neutral pions in a slice of phase space. Although these measurements are known to be very difficult, several experiments, in particular WA98 in the CERN Heavy Ion Beam[7] and MINIMAX in the FERMILAB Proton-Anti-Proton Beam[8], have attempted to discover DDC formation on the basis of the isospin ratio. Until now there were no positive results to corroborate the original CENTAURO events, measured two decades ago in high energy cosmic ray collisions [9]. The MINIMAX analysis, although not yet successful in proving the existence of DCC's, lead to the generation of independent cut parameters to reduce the background in the data sample.

In James Symons' contribution [10] to this conference presents the possibility of measuring the number of neutral pions with the STAR detector at RHIC. Because of the large particle density at RHIC energies (around 1500 pions per unit rapidity), measurements of DCC formation can be performed on an event-by-event basis.

The goal of our study was to determine the survival probabilities of signatures of domain formation in basic charged particle observables, namely the momentum space parameters (transverse momentum and rapidity) and the coordinate space parameters (emission angle in azimuth and in pseudo-rapidity). The underlying assumption is that, if the domains stay confined to a certain phase space bin, the emission of pions should lead to non-statistical structures in the charged pion distributions on an event-by-event basis. Therefore a multi-dimensional moment analysis should lead to unambiguous signatures. Generally, DCC domains should stay localized in coordinate space and in momentum space due to collective motion during the hadronization phase. Still, the effects of final state interactions on any hadronic signature have to be taken into account. By using a dynamical transport code we try to show whether chirally disoriented domains can survive the hadronization and rescattering phases in a central relativistic heavy ion collision. A successful measurement of such domains after freeze-out will depend on the domain size, its localization in coordinate space and the manifestation of the disorientation at low transverse momentum. We therefore investigated the measurement of the transverse momentum, the rapidity spectrum and the pseudo-rapidity spectrum of pions below 200 MeV/c. To simulate a realistic detector configuration we chose the STAR setup for RHIC, in particular the tracking detector configuration of TPC and SVT, which is sensitive to very low transverse momentum charged particles.

The complete simulation chain consists of:

a.) generating a DCC domain.

b.) embedding the domain in the background of a standard Au-Au event at RHIC (in our case we chose HIJING [11] events).

c.) propagating the domain through the hadronization via a dynamical transport code.

The domain generation depends strongly on the domain parameters, in particular the domain size and the energy density in the domain. Those two parameters will determine the number and the momentum spectrum of the pions in the domain.

The propagation depends strongly on the relative hadronization time of the domain in comparison to the background pions.

The next section tries to give a theoretical justification for the parameters we have chosen for our study.

Domain Size:

For a second order equilibrium transition we expect the domain size to be about the correlation length. The mass of the pion sets the maximum correlation length to be around 1/135 MeV/c^2. These domains will be too small to be detected.

If the equilibrium transition is first order, then in principle we can expect larger domains and Kapusta and Vischer showed that by using Bjorken hydrodynamics and relativistic nucleation theory [12] one can obtain sizeable domains. Still, at present, the second order phase transition seems to be more realistic, based on lattice gauge calculations. Generally second order transitions will not lead to large domains if the plasma hadronizes slowly and always stays close to chemical and thermal equilibrium.

For second order transition non-equilibrium transitions, Rajagopal and Wilczek suggested the quench scenario in which the plasma cools very rapidly [13, 4]. A non-equilibrium situation could be caused by significant supercooling before plasma hadronization. During the cooling long wavelength modes of the pionic field grow exponentially (spinodal decomposition). Gavin et al.[14] and Boyanovsky et al. [15] showed independently that this exponential growth has a natural slowing process which leads again to relatively small but probably detectable domains (r = 2-3 fm). Although the quench scenario is not very likely, in particular because the plasma cooling should be slow compared to the de-excitation of the chiral field, in heavy ion collisions the rapid longitudinal expansion during hadronization of the quark-gluon phase may lead to sizeable disoriented configurations of the vacuum.

To explore the role of the medium in domain formation, Gavin and Müller studied the dynamical evolution of the condensate in the presence of a nonequilibrium bath of quasiparticles [16]. The three-dimensional expansion of the heat bath changed the effective potential rapidly enough to create a quench-like condition. The size scale was for domains was found to be somewhat larger, perhaps $\sim 3-6$ fm, compared to fixed-geomerty quench simulations [14] and one-dimensional expansion. This result has been verified by simulations by Randrup [17].

Due to the relative uncertainty between the various non-equilibrium scenarios we chose a rather conservative domain size of 3 fm for most of the simulations.

It should be noted that based on the sigma model the average transverse momentum of the pions contained in the domain is radius dependent. The mean p_T is proportional to 1/r, which leads to a mean transverse momentum of about 100 MeV/c for a 3 fm domain radius. Fig. 1 shows the dependence of the spectral shape on the domain radius. The condensation clearly generates a strong low momentum enhancement, as was also pointed out by Ornik et al.[18].

Domain Energy Density:

If the domain formation proceeds slowly and therefore close to equilibrium, the available energy is given by the tilt of the potential rather than the actual potential maximum (top of the 'Mexican Hat').

In this case the energy density in a domain is defined to be

$$2m_\pi^2 f_\pi^2 \tag{1}$$

based on the explicit symmetry breaking term in the linear sigma model. This leads to a ΔV = 40 MeV/fm^3, which in return defines the number of pions in a domain to about

$$N = \Delta V \times 4\pi/3 \times r^3/m_\pi = 4500/140 = 32 pions, \tag{2}$$

assuming a 3 fm domain radius.

Figure 1. *DCC domain transverse momentum distribution as a function of domain radius.*

For a measurable effect, in particular in the environment of a central heavy ion collision, we have to assume that either larger domains are formed or that the energy density is enhanced due to plasma formation. An enhanced energy density is conceivable, in particular in the context of a sudden quench. Here the domain will start from a chirally symmetric distribution, which means it will start out from the highest point on the 'Mexican Hat' distribution. Therefore the domain in the condensed phase will absorb the full potential energy plus a kinetic energy contribution from the initial conditions which could easily raise the energy density to more than 100 MeV/fm^3.

Fig.2 shows the dependence of the number of pions on the energy density and the domain size. In the simulations we varied the energy density between reasonable minimum and the maximum values, based on the actual sigma model potential, to adjust the number of pions in the domain to a measurable level.

Figure 2. *Dependence of DCC strength (number of pions) on energy density and domain radius*

Hadronization Time:

The proper hadronization time for the pions generated in a central Au-Au collisions is set to be 1 fm/c, assuming a Bjorken evolution scenario.

Based on the dynamical treatment of the domain evolution within the linear σ model, Randrup [5] and Rajagopal [20] argue that it requires some time for the wavelength modes to oscillate and generate domains. In particular Randrup's contribution is very quantitative and shows that the typical domain takes about 4 fm/c to hadronize. During this time the domain will not undergo any final state interactions, which affects the survival probability, because the number of interactions is particle density dependent, and the expansion of the hadronized background will proceed between 1 fm/c and 4 fm/c to a level at which the interaction probability is seriously reduced. On the other hand it was pointed out by Kluger [19] that if one chooses a late proper hadronization time (e.g. $\tau \geq 2$ fm/c) the probability of domain formation and in particular domain growth might actually decrease accordingly.

For our simulations we set the hadronization time of domain and background to the same value, namely 1 fm/c, which should be regarded as worst case scenario, based on the dynamical mean field simulations mentioned above.

RESULTS

The dynamic transport code employed in these calculations was written by T. Humanic and is described in detail elsewhere [21]. The code is a kinetic model chosen to describe the evolution of the system after hadronization. Rescattering is simulated using a Monte Carlo cascade calculation which assumes strong binary collisions between hadrons. Besides more common hadrons such as pions, kaons, and nucleons, the calculation also includes the ρ, ω, η, η', ϕ, Δ, and K*-resonances. Resonances can be present at hadronization and also can be produced as a result of rescattering. Relativistic kinematics is used throughout. Isospin-averaged scattering cross sections are taken from Prakash et al.[22]. The domain itself is embedded into the hadronic background at the proper hadronization time. The subsequent transport code is a boost invariant model which follows the expansion rules of a Bjorken inside-outside cascade.

Our main calculation is based on 150 charged pions in a single domain with an average transverse momentum of about 100 MeV/c. Based on Fig. 2, these conditions can be accomplished either through an energy density of 150 MeV/fm^3 at the minimal measurable domain size (3 fm) or a 6 fm domain at the minimal available energy density (30 MeV/fm^3). The initial domain size determines the initial pseudo-rapidity distribution, therefore the 3 fm domain is preferred to confine the domain to a small bin in configuration space. Assuming that the domain is confined within the acceptance of the STAR detector tracking system (η=$\pm$1) the background contains around 1500 charged pions at the maximum efficiency. The unfavorable signal-to-noise ratio of 1:10, can be improved by correlating the pseudo-rapidity distribution with the transverse momentum distribution, see Fig.8. Our initial intent, though, was to detect the domain by simply analyzing the pseudo-rapidity spectrum itself. Fig.3(a) shows the spectrum of all charged pions in the STAR detector acceptance, assuming that the domain stays confined to r = 3 fm until freeze-out and does not undergo rescattering. Fig.3(b) shows the result of the transport code, including rescattering, applied to the same single Au-Au event. Obviously the low momentum pions scatter and the domain is diluted. Based on the statistical error in an event-by-event measurement (around 7%), the domain can not be detected at this level without using more sophisticated analysis procedures.

We decided to apply a method, first suggested by Huang et al., which is based on

Figure 3. *DCC rapidity distribution with and without rescattering in a central Au-Au heavy ion collision at RHIC (as simulated by HIJING)*

multi-dimensional wavelet transformation. The method is described in detail elsewhere [23], but the main way of scanning the distribution is by assigning a wavelet function to represent the data. Wavelet functions are invertible and orthogonal and are used to represent spiky distribution, in contrast to Fourier transforms which are used to parameterize smooth deviations. In this case the pseudo-rapidity distribution is described by a mother function (general distribution) and a father function (deviations from general distribution), which leads to a multi resolution moment analysis in which the coefficient of the father function is a measure of the size of the effect to be measured.

$$f(\eta) = f^J(\eta) = \sum_{k=0}^{2^{j-1}-1} f_{j-1,k}\phi_{j-1,k}(\eta) + \sum_{k=0}^{2^{j-1}-1} F_{j-1,k}\psi_{j-1,k}(\eta) \tag{3}$$

$\mathrm{f}_{j-1,k}$ is the mother function coefficient and $\mathrm{F}_{j-1,k}$ is the father function coefficient. The parameter j is determined by the resolution scale, k denotes the position at each scale.

The wavelet equation used in this analysis has a Haar Basis. Whether another Basis might be better suited to measure the effect will depend on further studies. For other more general references regarding wavelet analysis we refer the reader to a paper by J. Randrup [24] and the references therein.

The power spectrum of the father function coefficients is a measure for the size of the deviation from a smooth distribution.

$$P_j = 1/2^j \sum_{k=0}^{2^j-1} \mid F_{jk} \mid^2 \tag{4}$$

The higher the power of the father function coefficients the larger the deviation from the non-disturbed distribution. The pseudo-rapidity space is scanned in defined step sizes which relate to the size of the deviation. Even pure event generator events

Figure 4. *a.)Multi-resolution analysis for the rapidity distributions shown in Fig. 3 plus an undisturbed HIJING event. b.) Variation in multi-resolution analysis as a function of energy density in an r=3 fm DCC domain*

(e.g. HIJING central Au-Au) have non zero coefficients due to the statistical fluctuations on an event-by-event basis. In addition, the detector resolution adds another potential deviation to an ideal smooth distribution.

This analysis utilizes the size and the location of a domain simultaneously for identification purposes. We apply the analysis on an event-by-event basis which is slightly different form the original paper [23]. Here the deviation of the power spectrum is not an averaged effect on a data sample but rather describes the deviation of a single cell from the background as defined by the non-perturbed remainder of the pseudo-rapidity distribution. Therefore a very large domain (larger than the resolution scale = 2 units of η) or a complete condensation will not lead to a measurable effect with this method.

Fig. 4a shows the result of the wavelet analysis applied to the distributions shown in Fig. 3 and to a standard single event HIJING distribution. The wavelet analysis allows to determine a domain of size 3 fm and energy density about 100 MeV/fm^3 even after rescattering. The general x-scale, the step size of the binning, is translated into a pseudo-rapidity scale. After rescattering the domain covers around 0.5 units, whereas before rescattering the domain was confined to about 0.3 units. Although the re-scattering weakens the domain it does not fully destroy its main feature namely its confinement to a rather small bin in configuration space.

A more general simulation, which shows the dependence of the detectability of domains based on their respective size and energy density is shown in Fig. 4b. We conclude that at a nominal domain size of 3 fm, domains with an energy density as low as 50 MeV/fm^3 can be detected via a wavelet analysis even after re-scattering.

An additional effect, though not included in this calculation, that might contribute to the survival probability of the domain is Bose cascading. This effect was first observed in condensed matter [25], but it seems to affect the heavy ion spectra as well. A

Figure 5. *Comparison of rapidity distributions of DCC pions as a function of the relative distance in configuration space between the domain center and the surface of the fireball.*

recent evaluation of the effect of Bose kinetics on the low momentum part of the pion spectrum can be found in [26]. The authors conclude that the effect of Bose enhanced scattering leads to a doubling of the pion cross section for momenta below 100 MeV/c in central heavy ion collisions at CERN fixed target energies. Therefore we might observe two competing effects in the resulting spectrum. Low momentum domain pions rescattering from higher momentum target matter gain momentum, but in parallel part of the spectator matter is cascading to lower momenta. Therefore the number of particles at very low momentum stays almost constant and their rapidity distribution increases only slightly in width. A detailed simulation of this effect is underway [27].

The amount of rescattering depends strongly on the location of the domain in configuration space at the time of domain formation. In our study we place the domain in the center of the fireball at the proper hadronization time. Fig. 5 displays the pseudo-rapidity distribution of DCC pions for a standard domain (r = 3 fm, ϵ = 100 MeV/fm^3) at freeze-out as a function of the relative distance of the domain center from the surface of the fireball in configuration space at the time of domain hadronization. The domain undergoes lesser re-scattering the further inside the fireball it is created, which subsequently leads to a more confined pseudo-rapidity distribution for domains produced in the core of the fireball. This is due the kinematics of the domain particles with respect to the fireball particles. The low momentum domain pions expand slower than the fireball pions, and therefore decouple early from the fireball. A domain at the fringes of the fireball, though, will experience the most final state interactions, because the radially expanding fireball will traverse through the domain before decoupling and freeze-out.

A recent study by V.Koch [27] shows that in his transport model domains can not survive the rescattering. In these instances, the domains were placed at the surface of the fireball in the rest frame of the fireball. Based on our studies we conclude that a domain in the center of the fireball will freeze out first and therefore experience the

Figure 6. *Freeze-out time for various components of the pion spectrum*

fewest final state interaction. We therefore believe that the results from Koch and also results presented by the RQMD group at Quark Matter 97 are not necessarily incompatible with our simulations.

To further investigate the domain kinematics we compare in Fig. 6 the freeze-out time distribution of the pions in the hadronic background and the domain pions. On average the low momentum pions freeze-out faster, which at first seems counterintuitive. The slower particles should have more interactions for they stay longer in the interaction zone. This effect is reversed though for the very slowest particles. In this instance the fireball traverses through the pions which remain almost at rest. Therefore, the interaction zone decouples after a few tens of fm/c from the pions of interest. This might be one of the reasons that leads to a high survival probability for DCC's throughout the re-scattering phase.

It is worthwhile pointing out that an increase in the hadronization time for the domain itself will certainly lead to an increased survival probability. Assuming that the simulations by Rajagopal and Randrup are correct we can expect hadronization times as large as 5 fm/c. From the freeze-out time spectrum (Fig. 6) we deduce that the DCC pions have a freeze-out time of around 10 fm/c. Most of the final state interactions will occur in the very early part of the fireball hadronization, which means that late hadronization of the domains will lead to very large survival probabilities. In addition the domain freeze-out time will depend on the spatial position of the domain with respect to the fireball (see Fig. 6).

Fig.7 shows the effect of the rescattered domain on the transverse momentum spectrum. Fig.7(a) shows the transverse momentum spectrum of positively charged pions in the pseudo-rapidity range from -1 to +1 for a single central Au-Au collision. About 900 pions of a single isospin are found within two units of pseudorapidity. Fig.7(b) shows the same event including our standard DDC domain at freeze-out, after rescattering. The original number of 150 pions stays confined to the low momentum region. The ratio of "DCC" to "standard" pions below p_T=150 MeV/c is about 2:1, an enhancement

Figure 7. *Comparison of the transverse momentum spectrum of positively charged pions in the two central units of pseudo-rapidity with and without a standard DCC domain*

which should be detectable with any tracking detector with modest tracking efficiency below 100 MeV/c. The mean of the distribution shifts from about 330 MeV/c to 300 MeV/c. A shift in the mean could be evaluated sufficiently fast to serve as a trigger signal for DCC detection. The strong confinement in momentum space can also be used as an additional constraint on the multi-dimensional analysis of the pseudo-rapidity spectrum.

It should be pointed out that our simulations are based on the formation of a single domain at the center of the fireball. In a sense the formation of a single domain is highly unlikely. If the effect of chiral disorientation occurs one would expect many domains to be formed. As soon as the domain separation decreases below the size of the scattered domain as simulated in our code, the effect in the pseudo-rapidity spectrum will be lost due to domain merging. This effect is well described by the Central Limit Theorem. On the other hand each single domain will contribute to the low momentum enhancement in the transverse momentum spectrum. Therefore the production of multiple domains should lead to a stronger shift of the mean p_T and to a stronger shape change of the spectrum towards lower p_T.

In Fig. 8 we show two-dimensional distributions based on a simulation with five equally sized domains in a central Au-Au HIJING event. The figure tries to qualitatively compare the configuration space and momentum space distributions of pions after 10 fm/c for an event with domains (a+c) and an event without domain (b+d). It seems possible that by correlating the information from the spatial measurements (azimuth and pseudo-rapidity distributions) with the information from the momentum measurements one might be able to characterize events independent of the number of domains per event.

Figure 8. *Distribution of a HIJING event with and without domains in configuration (a+c) and momentum space (b+d). The momentum space exhibits strong low momentum components correlated with large fluctuations in configuration space.*

CONCLUSIONS

Based on a realistic dynamic transport code applied to relativistic heavy ion collisions which contain domains of disoriented chiral condensate and/or simple Bose condensates we conclude that low momentum particle domains can survive hadronic final state interactions. Their detectability will depend on the number of pions in the domain which in return depends on the domain size and the energy density inside the domain. For the detector resolution applicable to the STAR detector at RHIC we conclude that by applying a multi-resolution analysis 3 fm radius domains can be detected on an event by event basis if the energy density inside the domain exceeds 50 MeV/fm^3. If the domain size increases, the energy density threshold can be lowered accordingly. The formation of DCC's affects two event-by-event observables, namely the pseudo-rapidity and transverse momentum distributions of the charged pions. Multi domain generation in a single event might lead to a reduction of the effect in the pseudo-rapidity distribution, but it will lead to an enhancement of the effect in the momentum distribution. Multi-dimensional correlation studies which employ cuts in momentum and in configuration space should therefore lead to conclusive results concerning the existence of disoriented chiral domains, even without measuring the isospin dependence of the domain pions.

Therefore we strongly suggest that RHIC experiments put special emphasis on their low momentum coverage over a large range of pseudo-rapidity. Suggestions to use a topology trigger to trigger on non-statistical fluctuations in the rapidity distributions of charged particles will help to further select potential DCC events. At this point, both PHOBOS and STAR seem to be capable of measuring the effects of DCC formation in charged particle spectra.

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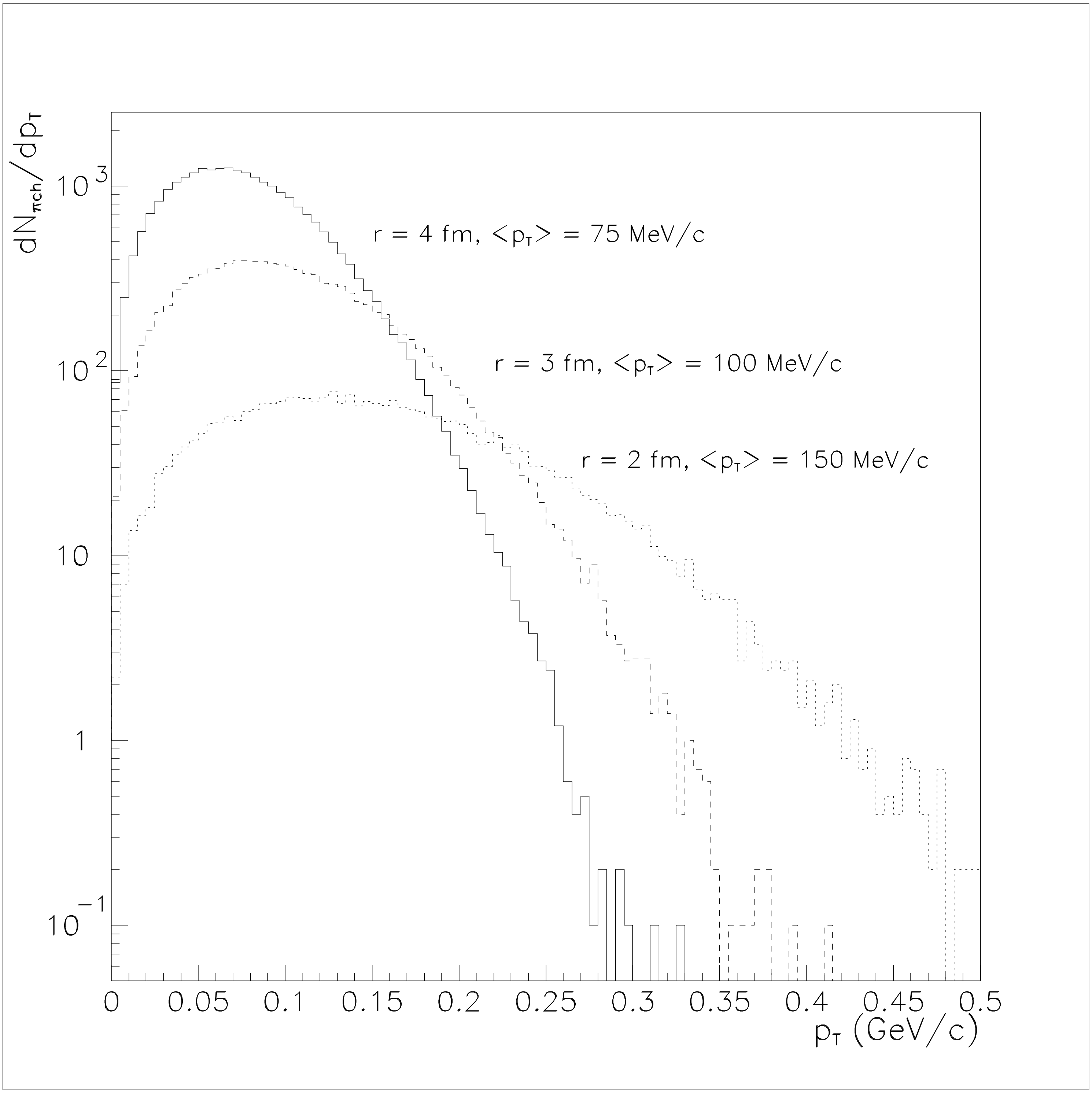
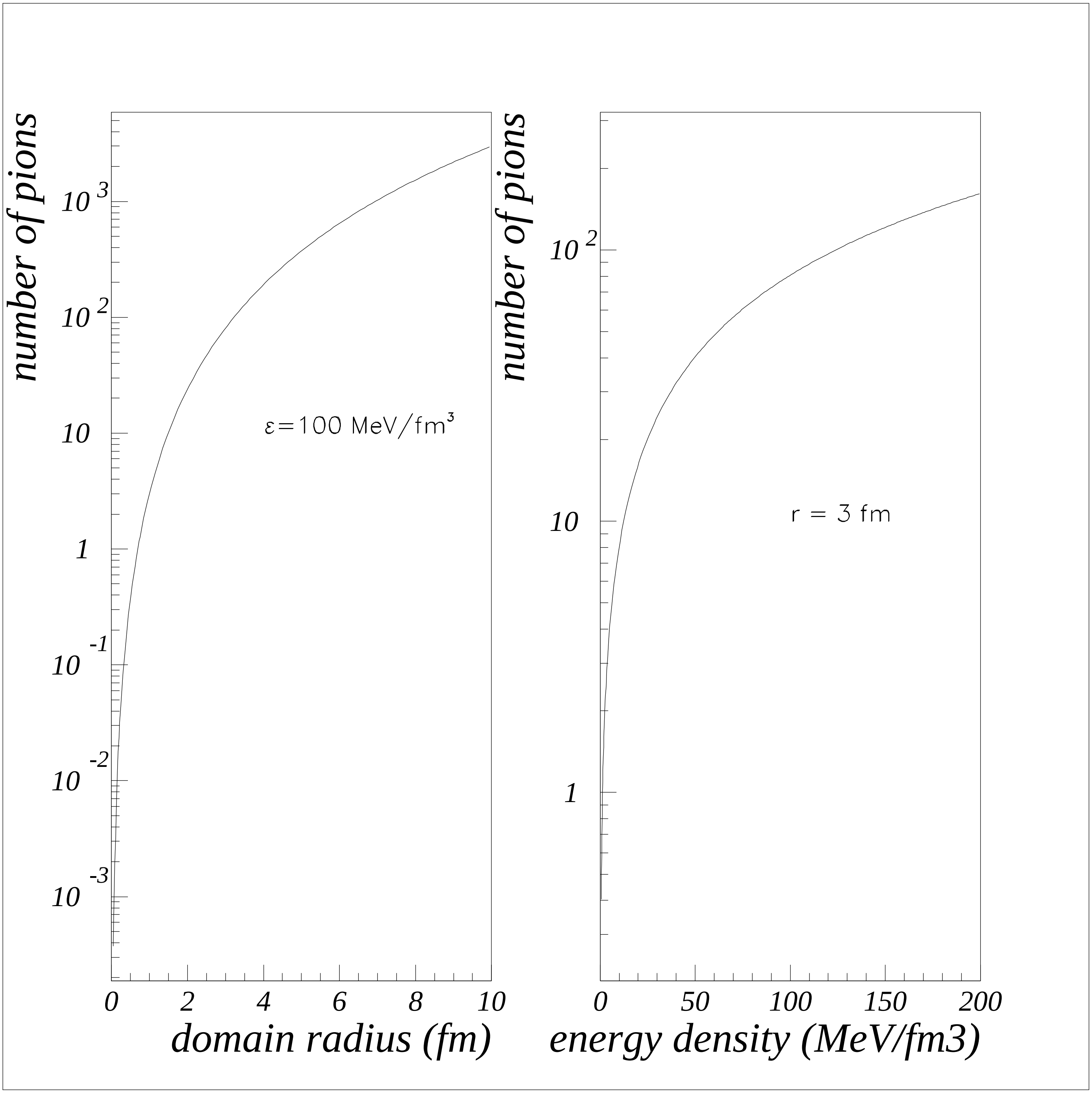
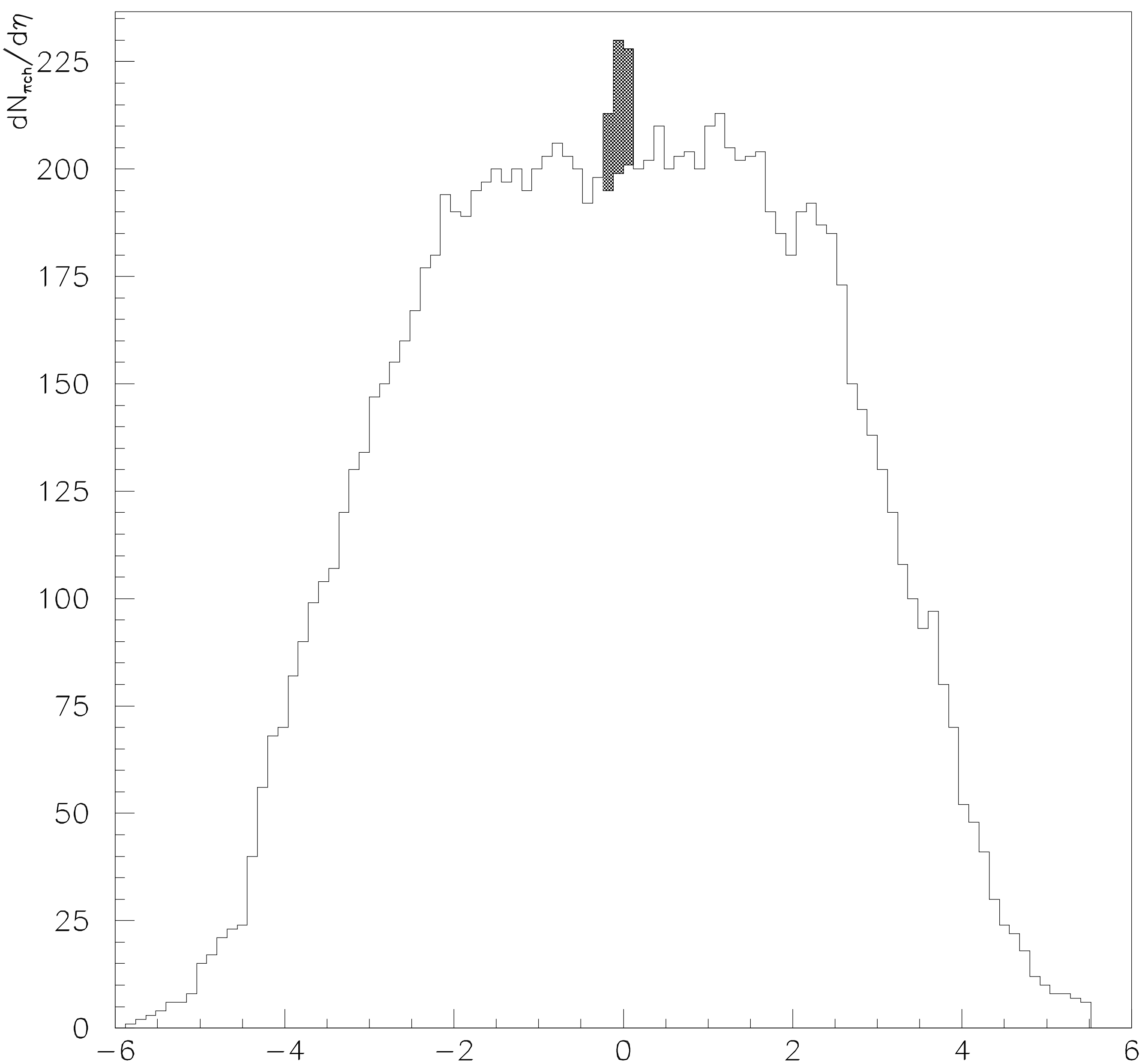


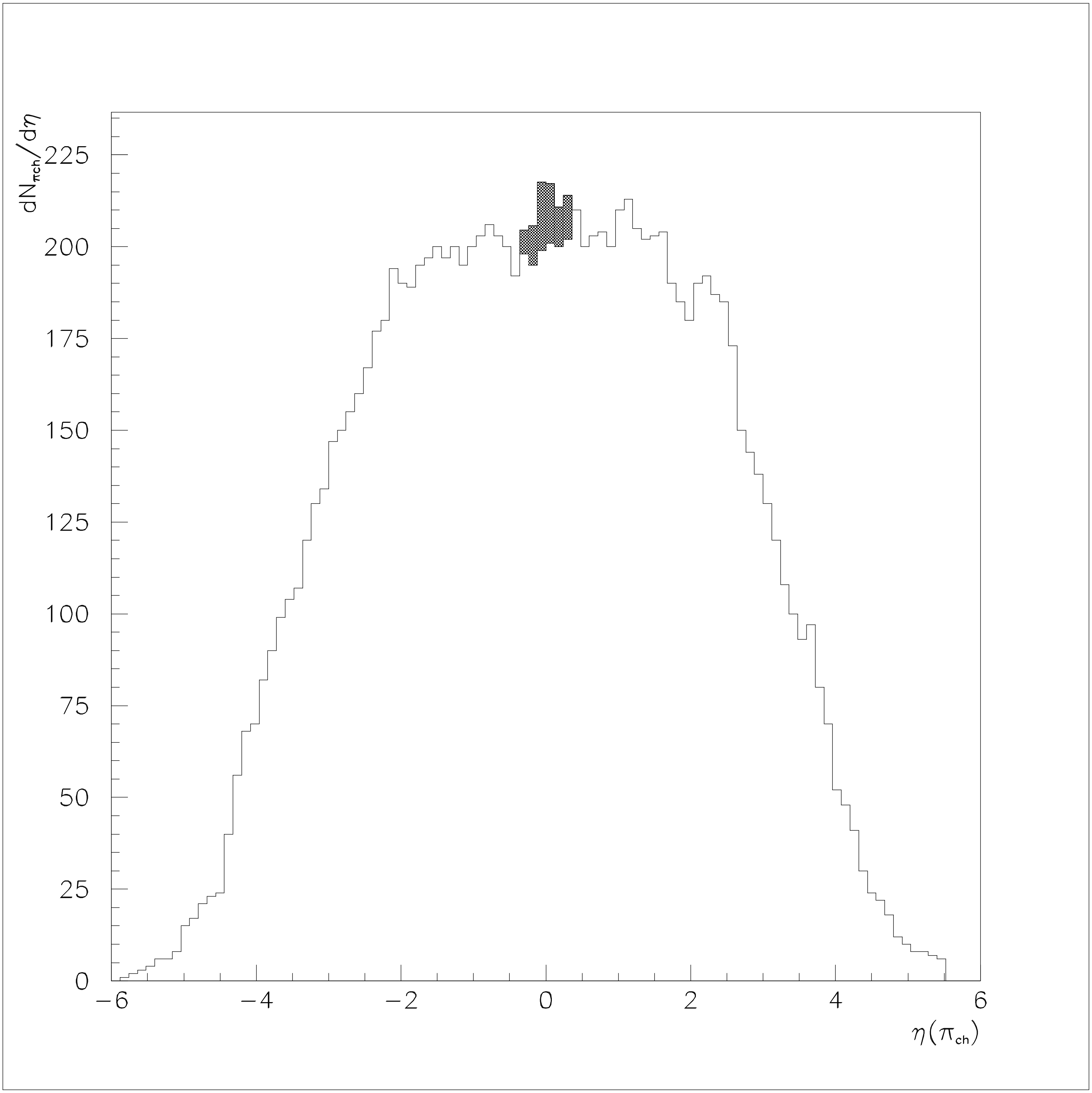
$dN_{\pi ch}/dp_T$
r = 4 fm, $\langle p_T \rangle$ = 75 MeV/c
r = 3 fm, $\langle p_T \rangle$ = 100 MeV/c
r = 2 fm, $\langle p_T \rangle$ = 150 MeV/c
10^3
10^2
10
1
10^{-1}
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
p_T (GeV/c)



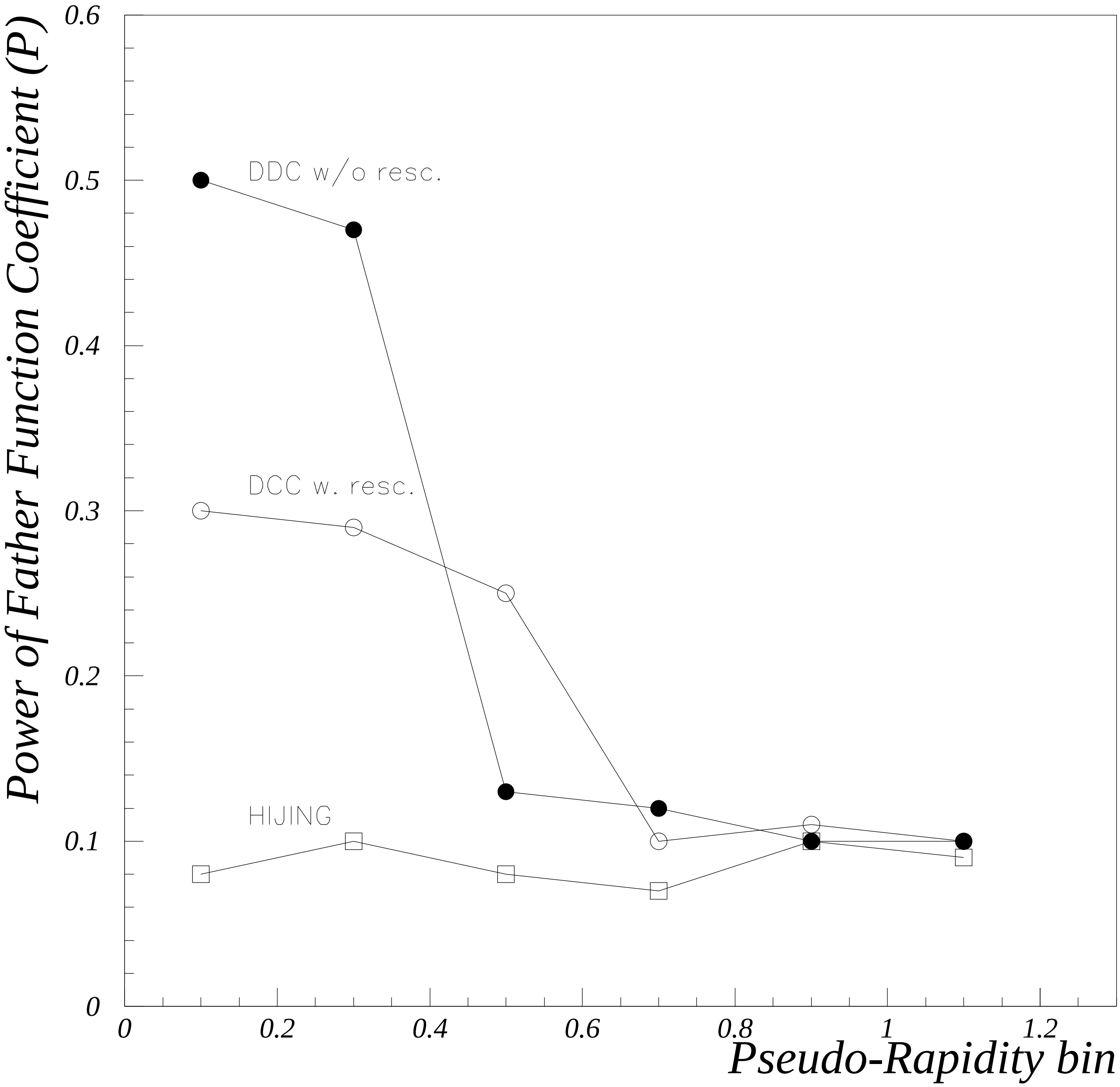
number of pions
ε=100 MeV/fm³
0
2
4
6
8
10
domain radius (fm)
number of pions
r = 3 fm
0
50
100
150
200
energy density (MeV/fm3)



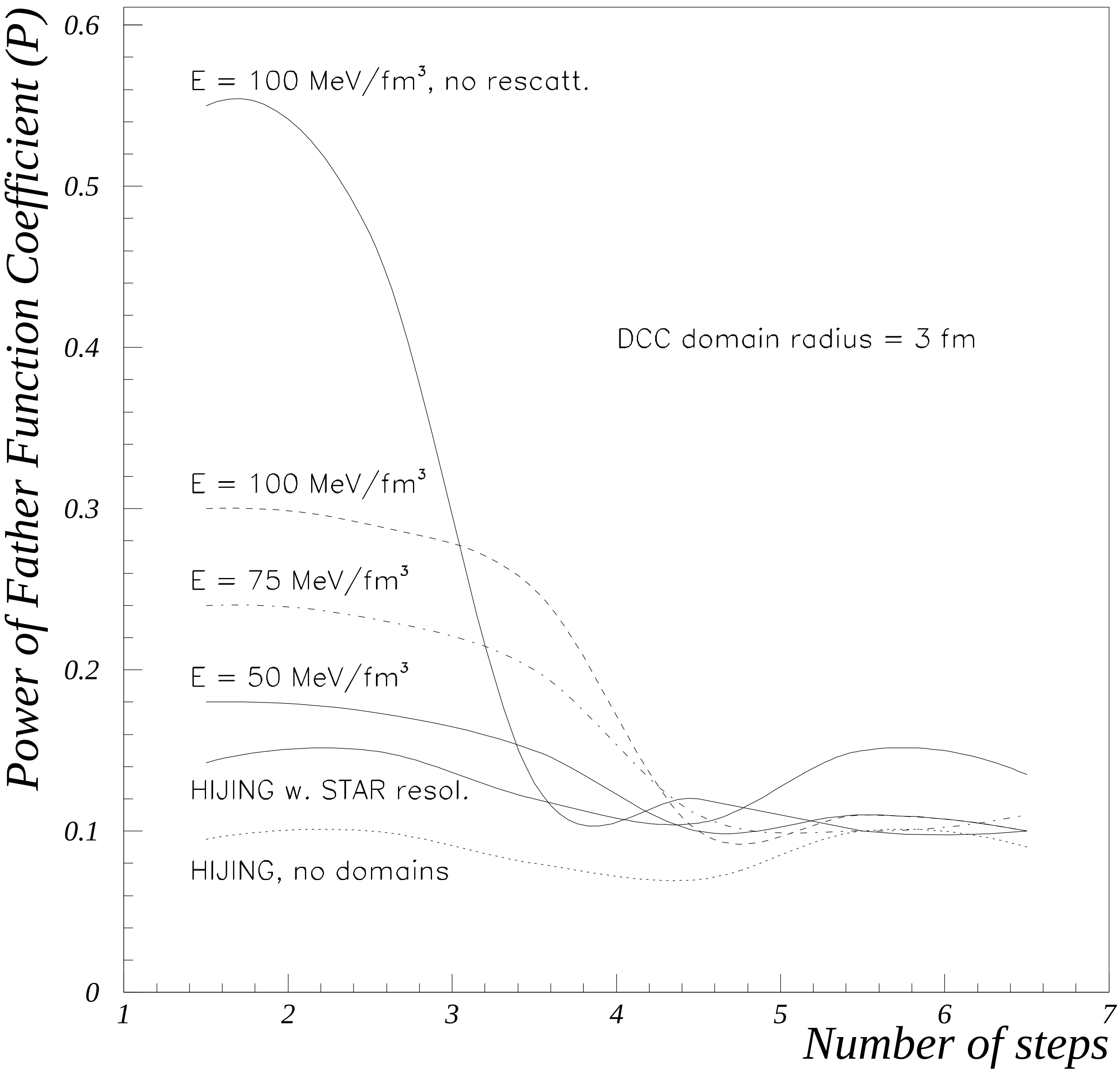
dN$_{\pi ch}$/dη
225
200
175
150
125
100
75
50
25
0
−6
−4
−2
0
2
4
6
$\eta(\pi_{ch})$



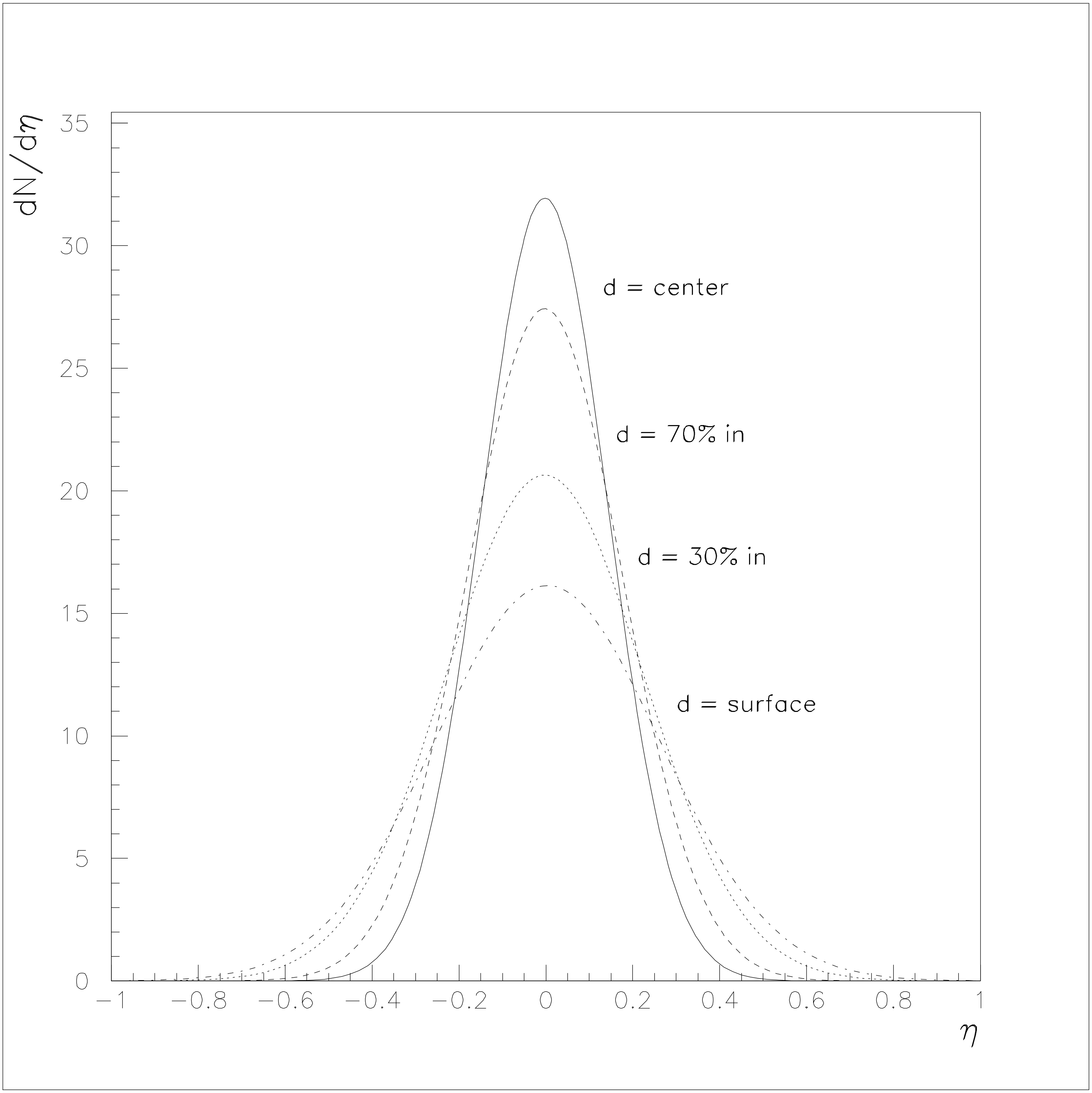
dN$_{\pi ch}$/dη
225
200
175
150
125
100
75
50
25
0
−6
−4
−2
0
2
4
6
$\eta(\pi_{ch})$



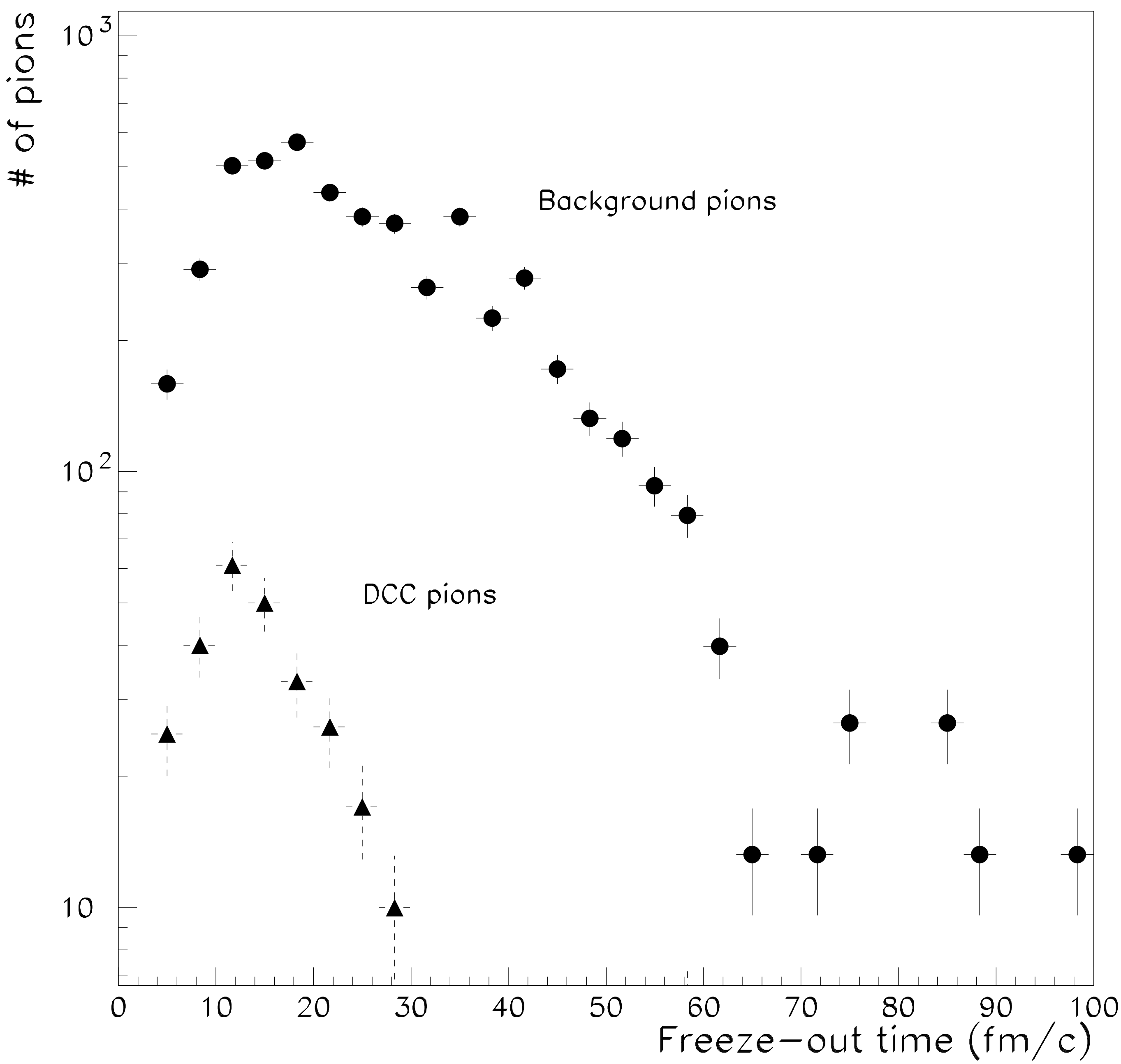
Power of Father Function Coefficient (P)
Pseudo-Rapidity bin
DDC w/o resc.
DCC w. resc.
HIJING
0
0.1
0.2
0.3
0.4
0.5
0.6
0
0.2
0.4
0.6
0.8
1
1.2



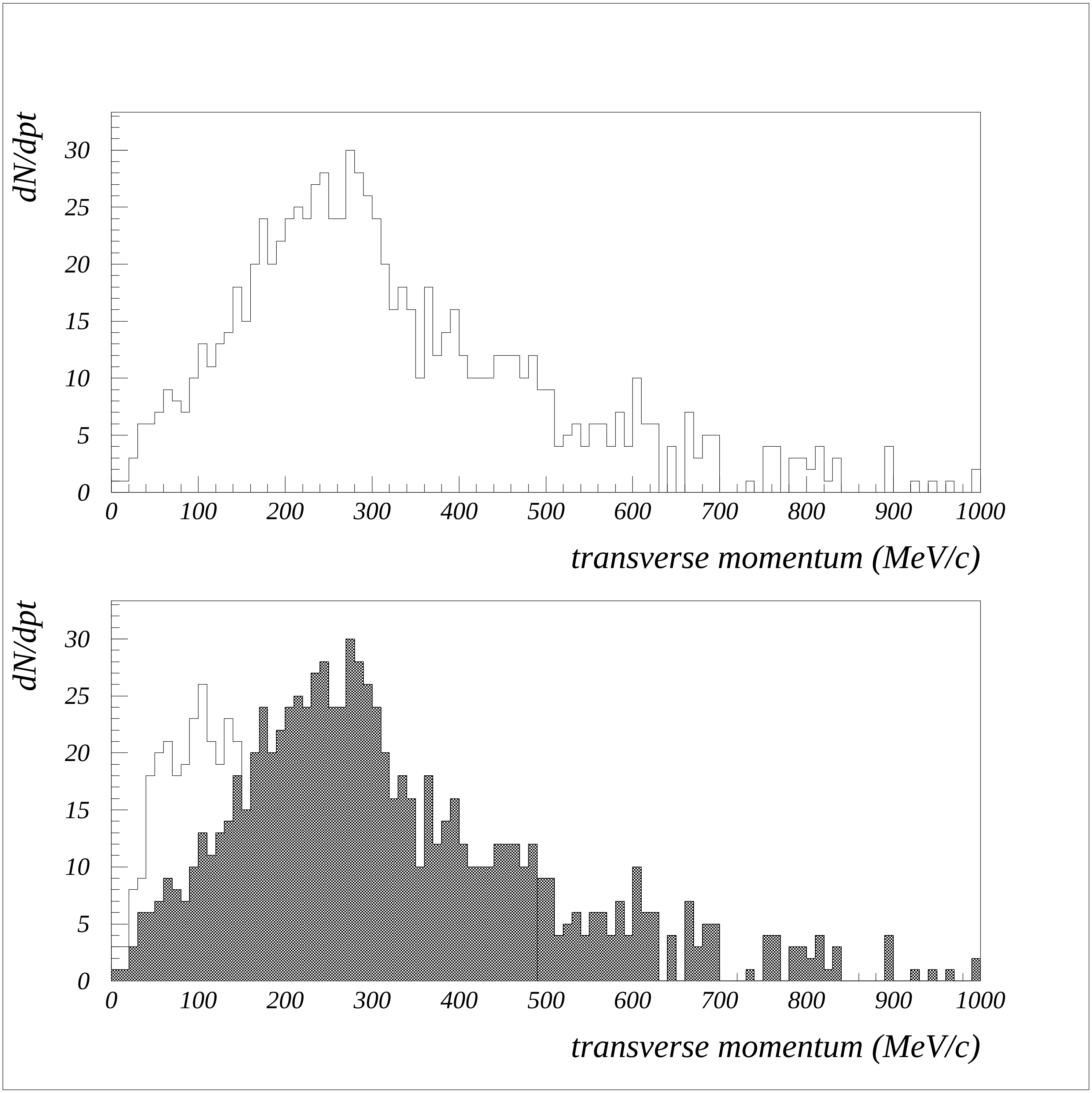
Power of Father Function Coefficient (P)
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
Number of steps
E = 100 MeV/fm³, no rescatt.
DCC domain radius = 3 fm
E = 100 MeV/fm³
E = 75 MeV/fm³
E = 50 MeV/fm³
HIJING w. STAR resol.
HIJING, no domains

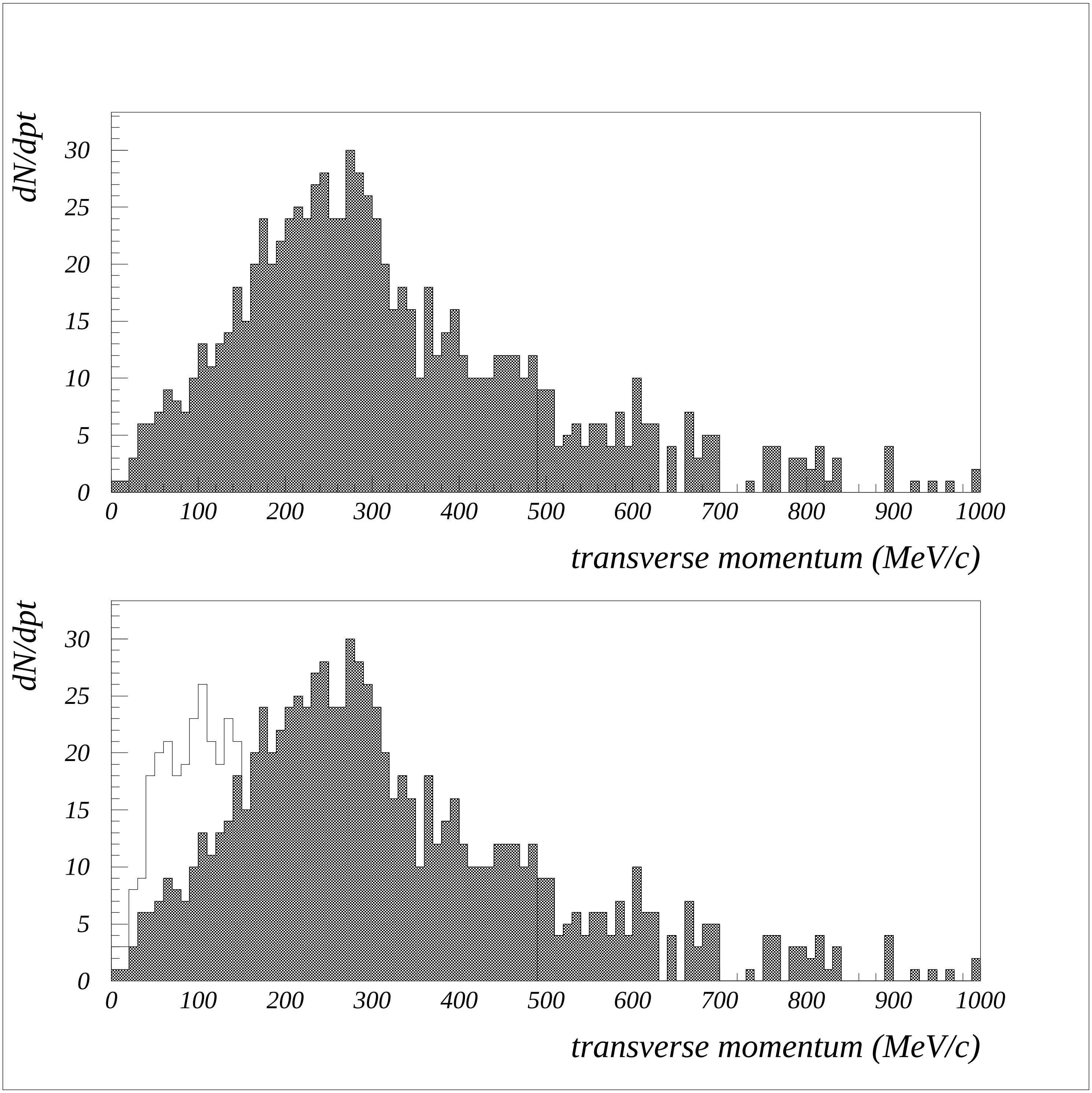


dN/dη
35
30
25
20
15
10
5
0
d = center
d = 70% in
d = 30% in
d = surface
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
η

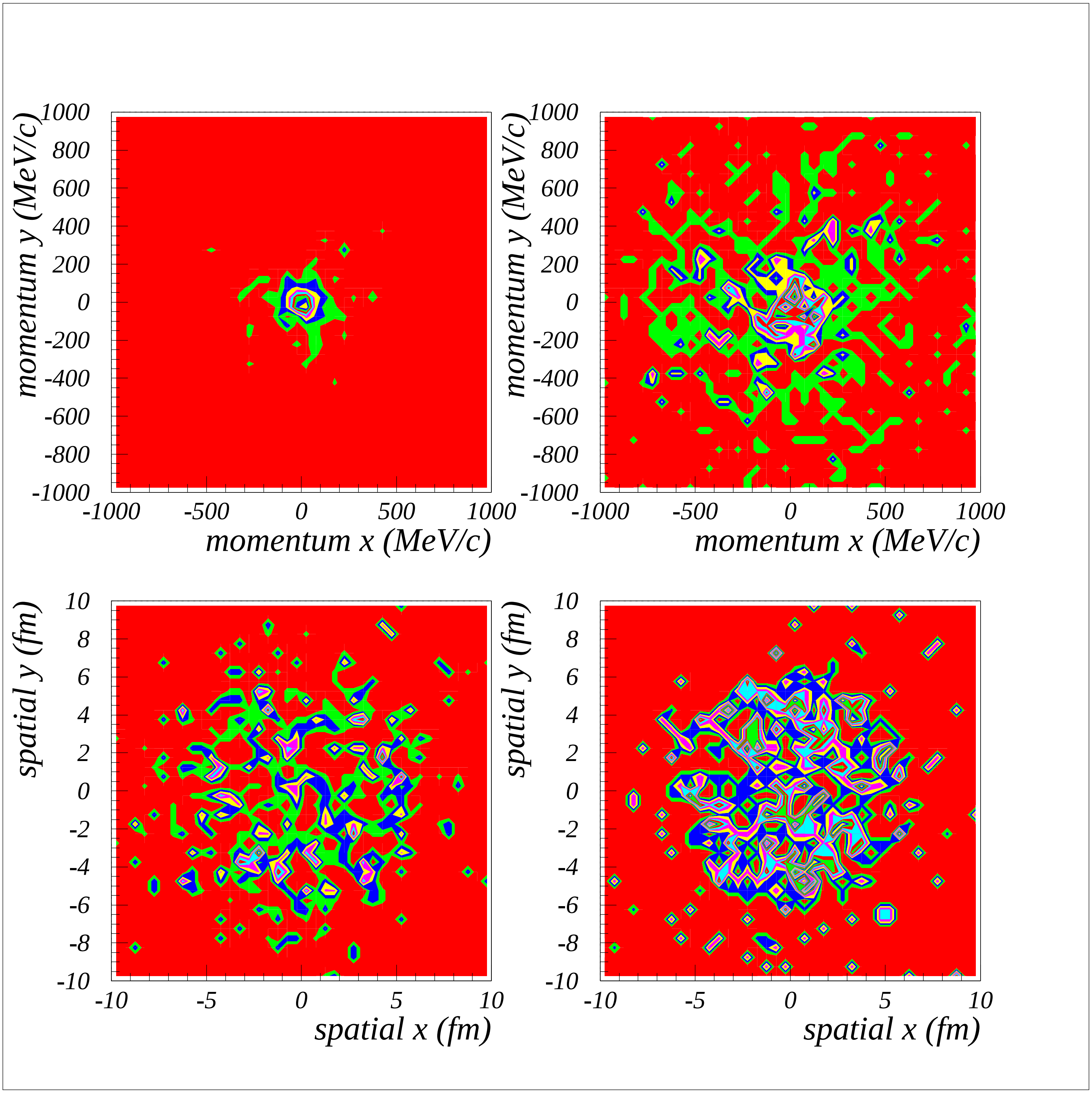


# of pions
10^3
10^2
10
Background pions
DCC pions
0
10
20
30
40
50
60
70
80
90
100
Freeze−out time (fm/c)


dN/dpt
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
1000
transverse momentum (MeV/c)
dN/dpt
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
1000
transverse momentum (MeV/c)



dN/dpt
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
1000
transverse momentum (MeV/c)
dN/dpt
30
25
20
15
10
5
0
0
100
200
300
400
500
600
700
800
900
1000
transverse momentum (MeV/c)



momentum y (MeV/c)
momentum x (MeV/c)
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1000
-500
0
500
1000
momentum y (MeV/c)
momentum x (MeV/c)
spatial y (fm)
spatial x (fm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-10
-5
0
5
10
spatial y (fm)
spatial x (fm)